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A fracture mechanics approach using Acoustic Emission Technique to investigate damage evolution in woven-ply thermoplastic structures at temperatures higher than glass transition temperature

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ABSTRACT

By means of a fracture mechanics-based approach, this work was aimed at investigating the damage evolution in 5-harness satin weave carbon fabrics reinforced PolyPhenylene Sulphide (PPS) structures at $T > T_g$ (glass transition temperature) when matrix toughness is significantly enhanced. Structures with a quasi-isotropic stacking sequence and a single-edge-notch geometry are characterized by an elastic-brittle response resulting from transverse matrix cracking and fibers breakage near the notch tip. Acoustic Emission (AE) activity is associated with these primary damage mechanisms, and the monitoring of AE signals is particularly relevant as it provides a reliable approach to quantify the strain energy release rate G_I as a function of the cumulative acoustic energy W_{AE}. In order to examine the correlation between AE energy and fracture energy, the coefficients of the model have been identified from the set of experimental data for one given ratio $\frac{a}{w}$. It therefore appears that the cumulative AE energy can be used as a damage criterion to determine the damage tolerance (through the evaluation of fracture energy) of a thermoplastic-based composite material. In addition, the definition of a macroscopic damage variable based on stiffness measurements and the evolution of the cumulative AE events may be used to investigate the fracture sequence and the damage kinetics. A power law independent from the loading conditions can be identified, and therefore be used to assess the severity of damage during loading. Finally, the correspondence in damage evolution given by the experimental AE data at microscopic scale and a cumulated damage variable at macroscopic scale validates the ability of both approaches to quantify the damage degree in fiber-reinforced PMCs, and to identify a critical threshold for damage initiation.

1. Introduction

The fracture behavior and damage tolerance of fiber-reinforced polymer matrix composite laminates significantly depends on the matrix toughness and the reinforcement architecture (woven or unidirectional ply). Fracture toughness is utmost important for structural applications as it represents the material capability to resist to fracture. Thus, researchers have become greatly interested in structural failure investigation, and fracture mechanics plays now an increasingly important role not only for academic interest but also for structural design as it provides valuable data during the design process.

In recent years, there has been a growing interest in using thermoplastic-based (TP) composites for structural applications in aeronautics because they are characterized by very interesting mechanical properties (good impact behavior, damage tolerance, fire resistance) and processing advantages (short autoclave cycles, no particular storage conditions) [1–4]. When it comes to damage tolerance, high-performance TP (e.g. PolyPhenyleneSulfide PPS - PolyEtherEtherKetone PEEK) matrix laminates are characterized by high values of fracture toughness compared to thermosetting-based composites. In addition, potential advantages of using woven-ply laminates as opposed to UD-ply laminates are discussed in the literature as woven-ply composites have higher values of interlaminar critical strain energy release rates G_{IC} (often more than 4–5 times) than the UD-ply laminates [1]. Most of the studies available in the literature deal with the mode I delamination of TP-

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based composites by means of double cantilever beam tests [5–10], and very few authors have investigated the influence of temperature [11]. Among the different experimental procedures classically used to estimate the fracture toughness, the instrumented Charpy impact testing is also often used [12], including the influence of test temperature on fracture energy [13].

1.1. Translaminar fracture toughness measurement

Fracture mechanics is usually characterized by many parameters (e.g. fracture toughness) that can be obtained from different experimental techniques applied to various testing conditions (tensile or bending loadings) and specific specimens geometry. Depending on the fracture behavior of the materials (e.g. brittle or ductile), a relevant fracture mechanics approach should be adopted. Thus, the assessment of fracture toughness for structural integrity can be achieved by many methods requiring a single-point value [14]. Basically, the fracture behavior of fiber-reinforced PMCs is described as ductile, brittle or quasi-brittle. Brittle or quasi-brittle fracture is associated with a rapid and unstable crack extension resulting from transverse matrix cracking and the sudden breakage of 0° oriented fibers.

From the macroscopic response standpoint (stress vs strain curve), a brittle fracture failure is characterized by a well-defined point of crack initiation, corresponding to a sudden drop in load, and provides a measurement of initiation fracture toughness K_{Init}. The critical value of fracture toughness K_C can be identified from the unstable crack propagation which can be identified from the *R*- or *J*-resistance curves. For design purposes, the *R*- or *J*-curves represent the increasing resistance of the material (in terms of strain energy release (*G* or *J*) for an increasing load, as the crack length grows (see Fig. 1). After the onset of crack extension, the initial part of *R*-or *J*-curves is associated with a stable crack growth prior unstable crack growth.

From the microscopic standpoint, the crack extension Δa is associated with different damage mechanisms depending on testing conditions (e.g. applied stress level, loading rate and temperature), the nature of constitutive elements (fibers + matrix), and the laminates stacking sequence. In the early stages of damage (at low stress levels), these micro-mechanisms absorb a small portion of the mechanical energy. As stress increases, damage grows and contributes to the dissipation of a larger portion of mechanical energy which can be measured by means of the strain energy release rate in standardized specimens, through the evaluation of the crack length (hence the created crack surface).

In laminates consisting of a ductile matrix system, ductile fracture is associated with a slow and stable crack extension. This type of fracture is characterized by a continuous extension of damage

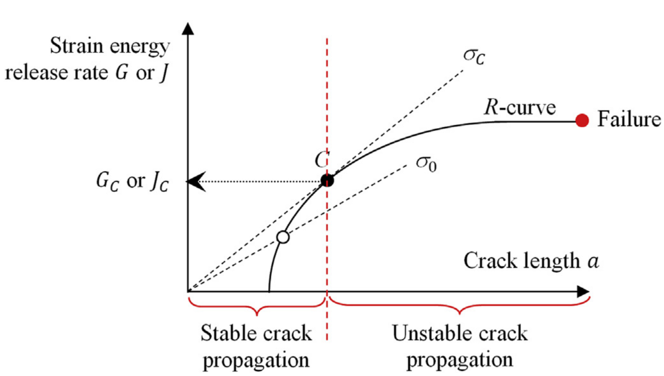

Fig. 1. Determination of the critical fracture toughness from *R*- or *J*-curves.

coming along with a ductile deformation rather than a point fracture. Such a fracture mode can also be quantified from *J*-resistance curves, which may result in some uncertainty due to the difficulty in localizing the fracture point due to plastic deformations. Ductile fracture initiation toughness K_{Init} can still be obtained from a typical point defined near the onset of stable crack growth and deduced from the *J*-resistance curve near the transition from initial crack blunting to crack extension which can be identified by a distinct change in the slope of the *J*-resistance curve [14]. Similarly to brittle fracture, the critical value of fracture toughness K_C can be identified from the unstable crack propagation. In ductile materials, instability of the crack propagation corresponds to the development of the plastic zone at the crack tip. Graphically, when the remote stress reaches a critical value σ_C, unstable crack propagation occurs as the crack driving force (represented by $\frac{dJ}{da}$) is higher than the slope of the *J*-resistance curve at the intersection point (see Fig. 1).

In orthotropic or quasi-isotropic composite laminates, transverse matrix cracking and fibers breakage (also known as translaminar failure modes) are usually the primary damage mechanisms occurring in the early phase of mechanical loading. A comprehensive review of techniques for the experimental characterization of the fracture toughness is given in Ref. [14], and in Ref. [15] when it comes to the translaminar failure mode of FRPs. When it comes to evaluate the mode I fracture toughness of FRPs, the translaminar fracture toughness can be estimated by means of Single-Edge-Notch structures [16–19]. However, translaminar fracture has received relatively little attention from the scientific community until now [20]. In FRPs, the fracture mechanics behavior is often studied by using the Linear Elastic Fracture Mechanics (LEFM) parameters: the critical strain energy release rate (G_{Ic}) and stress intensity factor (K_{Ic}), the *J*-integral, the crack opening displacement (COD), the J-resistance curve and *R*-curve analysis [21]. In fracture mechanics, the energy release rate *G* is one of the most fundamental parameters. It is defined as the rate of energy released by the crack growth. An important aspect of fracture resistance is that it may vary as the crack grows such that *G* is a function of the crack growth Δa [17]. Orthotropic and quasi-isotropic laminates are usually characterized by an elastic-brittle response. From the macroscopic response standpoint, in the case translaminar failure mode, crack initiation and propagation virtually occur at the same time corresponding to ultimate failure making therefore difficult the assessment of corresponding strain energy release rates. Indeed, once they are initiated, cracks will propagate very rapidly until ultimate failure. In the ideal case (linear elastic-brittle response), an abrupt drop in load at the moment of crack initiation occurs. Since it is difficult to precisely measure the length of the crack at the peak load (and therefore the compliance) in the polymer composites, Crack Tip Opening Displacement (CTOD) measurements are often used to investigate damage evolution [21].

1.2. Correlation between AE energy and mechanical energy

To characterize damage mechanisms and investigate their evolution in FRPs, many *in situ* and non-destructive evaluation techniques have been implemented. Acoustic Emission (AE) techniques are often used to detect the onset and growth of microscopic failure in composite materials [22–24], and many attempts have been made to distinguish between different types of failure [25–31]. Among the different approaches developed Modal Acoustic Emission (MAE) and peak frequency analysis of generated AE waveforms, proved to be very effective to characterize damage types as it was shown recently by Baker et al. who have studied the initiation and propagation of cracks in CFR epoxy laminates using MAE and waveform energies, coupled with peak frequency data correlated to